CURRENT PROPAGATION BETWEEN A PLASMA OPENING SWITCH AND A LOAD DURING OPENING

G.I. Dolgachev, Yu.G. Kalinin, A.S. Kingsep, A.G. Ushakov
Russian Research Center "Kurchatov Institute", Moscow 123182, Russia

R.J. Commisso, P.F. Ottinger, S.B. Swanekamp, B.V. Weber
Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375 USA

Abstract

During the initial stages of opening in a long-conduction-time (~ μs) plasma opening switch (POS), a current propagation phenomenon is observed between the POS and the load. In this paper, we review the experimental characterization of this current propagation phenomenon and summarize the models proposed to describe it. Our goal is to consider the physical scenario of POS operation, regardless to particular POS construction and parameters. At present moment, electron magnetohydrodynamics (EMHD) seems to be a good basis to describe the POS conduction phase which probably determines all the basic output characteristics of POS. Sometimes, however, the anomalous resistivity joins the game.

I. EXPERIMENTAL BASIS

As early as in 80-ths, it was found that conduction phase of POS were responsible for the characteristics of the opening phase. It was shown experimentally that the current/field penetration into a diode gap were happening in nondiffusive manner but in form of a steep wave looking like a shock wave. However, unlike real shock waves, the wave of magnetic field penetration did not include the motion of matter but only redistribution of the current flow. Starting from beginning of 90-ths, little by little, it became clear that not only POS plasma fill plays an important role in the switching scenario but also the downstream region intermediate between POS gap and load.

In Tomsk at the Institute of Electrophysics, experiments were carried out on the microsecond generator "Double" [1] with the following parameters: 0.533 μF capacitance, 0.7 μH inductance, and 480 kV output voltage. The vacuum coaxial line had cathode and anode diameters of 4.5 cm and 30 cm, respectively, an especial 500 nH section of such a line, short circuited at the end, served as the load. The current rise time and its amplitude were 2.5 μs and 150 kA, respectively. The plasma density was estimated as 10^{13} cm^{-3}. The velocity of plasma front reached 10-15 cm/μs. On the base of electrical and magnetic measurements, the authors concluded: 1) the conduction phase of their microsecond POS was characterized by a translation of the channel of enhanced current density toward the load; 2) most of the current in this channel were carried by electrons; 3) the maximum axial velocity of the current channel translation along the cathode was recorded during the last 50 ns of the conduction phase.

Similar results were obtained on DM1 at Maxwell/Physics International [2]. On DECADE Module 1, detailed measurements of the field/current propagation toward the load were carried out in both megavolt and megaampere ranges. A sketch of the POS-load region on DM1 is shown in Fig.1 reproduced from [2]. Plasma is
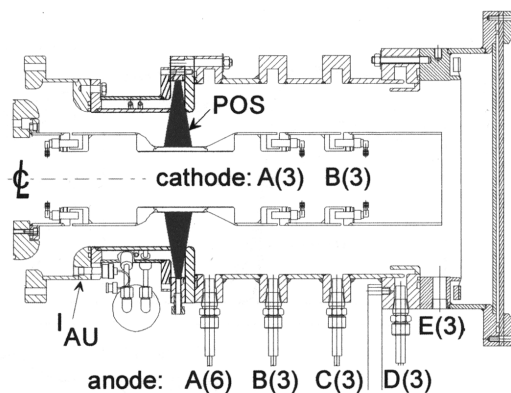

Figure 1. DM1 POS-load region instrumented with current probes.

injected between the inner and outer conductors a few μs prior to firing the generator using 12 plasma guns. Two gun configurations were used: 1) direct injection as shown in Fig.1 and 2) "manifold" injection, where the plasma was flowing through a 90° bend. The electron density was about 10^{15} cm^{-3} in the gap. The plasma was generated by a surface flashover of Teflon, producing ions of F, C, and probably H and O impurities.The center conductor radius in the POS region was 4.4 cm, increasing to 6.3 cm downstream. The plasma was injectedthrough a 2-cm long aperture. The electron-beam diode was used as a high impedance load in these experiments. The distance between the plasma guns and the load anode was 40 cm.

In Fig.2 also reproduced from [2], one can see the current waveforms for a typical shot. Each waveform is

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14. ABSTRACT
During the initial stages of opening in a longconduction- time (~ ìs) plasma opening switch (POS), a current propagation phenomenon is observed between the POS and the load. In this paper, we review the experimental characterization of this current propagation phenomenon and summarize the models proposed to describe it. Our goal is to consider the physical scenario of POS operation, regardless to particular POS construction and parameters. At present moment, electron magnetohydrodynamics (EMHD) seems to be a good basis to describe the POS conduction phase which probably determines all the basic output characteristics of POS. Sometimes, however, the anomalous resistivity joins the game.

15. SUBJECT TERMS

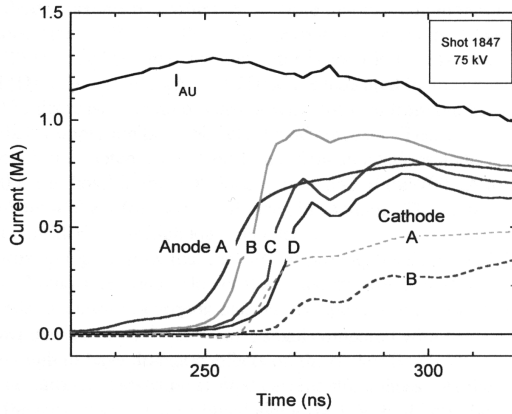| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **SAR**	18. NUMBER OF PAGES **4**	19a. NAME OF RESPONSIBLE PERSON
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Figure 2. Current waveforms for a typical shot with a high impedance load.

identified by a letter corresponding to those in Fig.1. Anode currents are indicated by solid lines and cathode currents by dashed lines. Note that cathode monitor A is at the same axial position as anode monitor B. Thus we may conclude that there exist a slant of the propagating current front just similar to that observed in [1]. The POS voltage has a maximum value 1.8 MV at t=290 ns. At this time the generator current reaches 1.2 MA, the anode monitor closest to the load (D) indicates 700 kA, and 250 kA is indicated by the cathode monitor closest to the load (B). About 500 kA were "lost" in the POS-load region, and of the 700 kA total current reaching the load anode, about 450 kA were flowing aside. The velocity of the current front propagation was estimated as ~ cm/ns. One can readily estimate this velocity being more than Alfven velocity, hence, there was a "tong" of rarified plasma propagating toward the load.

Further investigation of the problem was carried out on Hawk at NRL [3,4] on the current level up to 800 kA with many different POS plasma sources resulting in different plasma species. Experiments on Hawk showed difference in the dynamics of the travelling current channel for different conduction times and loads [3], and between single- and multiple-species POS plasmas [4]. Nevertheless, the basic effect was just the same, i.e., downstream current-carrying plasma motion toward the load.

At the Kurchatov Institute a rep-rate generator of electron beam with POS working in a single-pulsed mode was utilized for experiments [5]. Main generator parameters were as follows: 0.4 μF - primary Marx generator capacity, 170 kV - Marx output voltage, 1 μs - main circuit period, - 120 kA - generator current amplitude. Inner and outer POS electrode diameters were 14 and 160 mm respectively. To fill the interelectrode gap with plasma a set of 24 plasma guns have been used. Plasma guns were placed at the outer electrode of the vacuum coaxial line. In a high-impedance load mode the voltage multiplication coefficient was about 3-5. POS voltage was measured by both dB/dt loop and ohmic monitor ; ohmic shunts measured total current in the

circuit, and the load current. Conduction phase measurements were done with a use of dB/dt loops placed both at the cathode and at the anode downstream POS, cathode shunts - current monitors (Fig.3). Typical signal
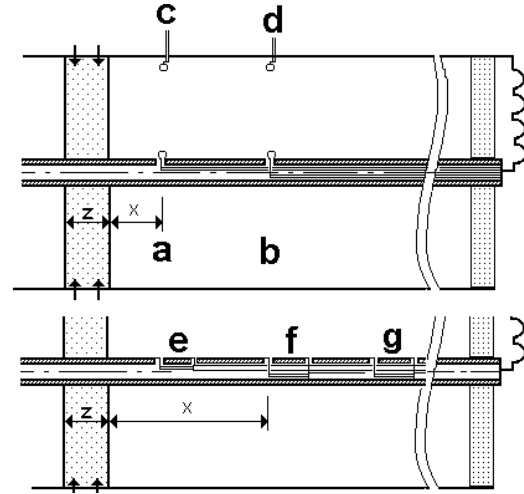

Figure 3. A schematic of probe location in the downstream POS region: a,b,c,d - dB/dt loops, placed at the central cathode and anode, 15 and 30 cm from initial plasma displacement; e,f,g – current monitors (shunts) placed at the cathode 15, 30, 45 cm from initial plasma displacement.

waveforms characterizing the pulse parameters are represented in Fig.4 for high-impedance an inductive load (0.1-0.4μH). Current and magnetic field wave parameters
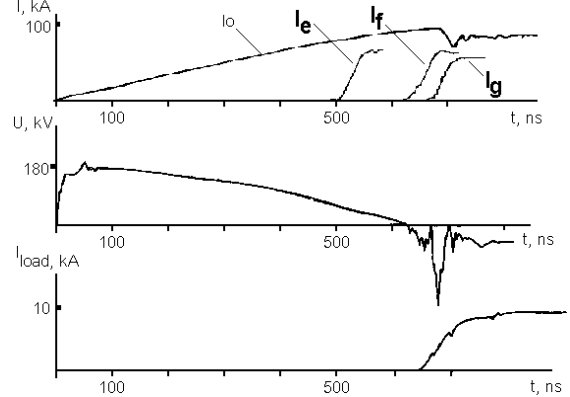

Figure 4. The generator current (I_0), POS voltage (U) and inductive load current (I_{load}) wave forms for a transmission line terminated by a vacuum inductance. I_e, I_f, I_g - time histories of cathode currents from monitors placed 15 and 45 cm from POS located as it is shown in Fig.3.

were measured for a conduction phase of the POS using dB/dt loops (Fig.3), placed at both cathode and anode. Current monitors (shunts) embedded in the cathode were used to measure cathode currents ("e","f","g" in Fig.3); they were placed 15, 30, 45 cm from plasma guns. They were made from 0.1 mm *SS* tube 20 mm length and 14 mm diameter. The shunts did not distort the cathode geometry. Fig.4 represents shunt signal waveforms.

Current channel velocity could be estimated analyzing the signal waveforms as near $5 \cdot 10^8$ cm/s at the end of conduction phase. Shunts capture approximately 80% of the total current, the rest 20% go through the plasma. Effect that was observed was again the magnetic field/current propagation in the form of rather steep front moving from the POS diode toward the load. While moving, this front becomes accelerated and acquires the maximal velocity just before the moment of switching. This conclusion coincides with that made in the paper [1]. Signals characterizing near-anode current penetration differ from cathode ones. Near-anode penetration (probes "c" and "d" in Fig.3) begins as soon as the drive current starts and after 500 ns a signal similar to the cathode one appears 50 ns delayed. Current front angle could be assessed from that delay as 50^0. Thereby the effect of the front slant observed in [1-3] was confirmed. The new effect was that of the front broadening, non-proportional to the acceleration but more slow. The latter unlike the acceleration, seems to be non-universal one that probably will be explained below.

II. SPECULATIONS AND ESTIMATES

The final stage of POS operation scenario is, normally, erosion phase. Even starting from the density $\sim 10^{15}$ cm^{-3}, we deal at last with very rarefied plasma fill in the gap that was confirmed, e.g., in [4] by the interferometric measurements. Space charge effects are typical of this phase which were thoroughly simulated in [6]. The group of effects we discuss in this paper relates to the previous, i.e., conduction phase. For this phase, EMHD effects [7] seem to be predominating. The experimental data cited above testify, with rather great probability, that a very important element of the switching scenario is the dilute plasma flow from the diode gap towards the load. If we dealt with the current channel located just on the front of this plasma propagation, the current front hardly could be so steep. So, the dilute plasma is probably repelled into the downstream region earlier than such a current/field propagation occurs. It is very difficult to give the analytical description of such a process, neither simulations could be very efficient, since space charge effects, EMHD, and MHD effects should be confused in such a process of expansion resulting in too complicated hierarchy of space and time scales. To consider the effect of the current channel propagation is much less difficult.

Effect of the field/current penetration into a well-conducting medium in the form of strong nonlinear wave (they often call it KMC-wave) was predicted within the frames EMHD and later revealed in experiments. POS in its conduction phase always corresponds to the EMHD window of parameters [7]:

$$V_{Te}, V_{Ae} \gg j/ne \gg c_S, V_A$$

$$\omega_{Be} \gg \tau \gg \omega_{Bi}$$

$$c/\omega_{pe} \ll \delta \ll c/\omega_{pi}$$

Here δ and τ are the space and time scale of the problem, respectively, all the rest terms are conventional. In our case $\delta \sim |\nabla \ln(nr^2)|^{-1}$. Typical KMC-wave looks as follows:

$$B = \frac{B_0}{2}\{1 - \tanh\frac{x - V_{KMC}t}{\Delta}\}, \qquad \text{where}$$

$$V_{KMC} \approx V_A \frac{c}{\omega_{pi}\delta} \gg V_A, \quad \Delta \approx \frac{ne\delta c^2}{\sigma}.$$

As one readily can see, magnetic front has to propagate much faster than the substantial flow, hence, we may put the density profile to be constant in time. As $V_{KMC} \propto n^{-1}$, it has to be accelerated while following decreasing density profile.

As for the broadening, let us remind, this effect seems to be less universal. Moreover, at first sight, the same formulas for the KMC front width result in steeping instead of broadening. However, it still can be explained by taking into account possible mechanism of anomalous resistivity [8]. In the dilute downstream plasmas, its manifestations are more than likely. However, its efficiency has to compete with classical resistivity in multi-charged plasmas. That is why such an effect is non-universal one. EMHD window of parameters corresponds, under the condition $B^2 \ll 4\pi nmc^2$, to the current-driven ion-acoustic instability as well. That was confirmed in our recent experiments[11]. In a regime with the total current I conditioned by the outer circuit only essentially nonlinear scenario of instability is available. Thus, the effective conductivity may be presented by the Sagdeev's formula: $\sigma \approx \omega_{pe}\frac{neV_{Te}}{j}$, or, what is the same, $\mathbf{j} \approx n^{3/4}eT^{1/4}m^{-1/2}\mathbf{E}$. Let us also take into account that current flow density is inversely proportional to the front width, $j \propto I/\Delta$. As a result, we obtain the following relation:

$$\Delta \approx \frac{ne\delta c^2}{\sigma} \propto \frac{nI}{n^{3/2}\Delta} \Rightarrow \Delta \propto n^{-1/4},$$

so, just the slow broadening of the front has to occur in the essentially nonlinear regime. The obvious manifestations of the regime of anomalous resistivity were obtained in [9] by means of the Stark measurements.

We believe, the massive of experimental information presented in some part in this paper, together with theoretical models developed, should provide the new level of understanding fast POS dynamics, necessary for the successful operation with POS as the technological device.

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